THE DRYING RATE OF SUGAR MAPLE AS AFFECTED BY RELATIVE HUMIDITY AND AIR VELOCITY

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THE DRYING RATE OF SUGAR MAPLE AS AFFECTED BY RELATIVE HUMIDITY AND AIR VELOCITY

By

O. W. TORGESON, Engineer

Introduction

Lumber dry kilns now in use vary from natural circulation kilns with hand control to the latest type of fan kilns with automatic control of both temperature and humidity. In between are remodeled kilns equipped with various types and sizes of fans, and various types of control.

Some slow circulation kilns are used for drying green stock where rapid circulation would be best, and some rapid circulation kilns are used for drying air-dried stock where a much slower rate would be satisfactory.

Circulation is needed to replace heat losses through walls and around doors and where these losses are large a brisk rate is helpful in maintaining uniform drying conditions. Another important consideration, however, is the supplying of heat for evaporation, and, therefore, more efficient designing and drying could be accomplished if more specific information was available concerning the air needs for various species and items.

How long does it take to kiln dry sugar maple? This seems like a simple question, but it can be answered satisfactorily only after many factors are taken into consideration. These factors are: (1) original and final moisture content, (2) sapwood or heartwood, (3) temperature of kiln air, (4) size of stock, (5) relative humidity of kiln air, (6) velocity of kiln air, and (7) length of air travel. To correlate various combinations of these factors and drying time requires considerable knowledge of the effect of each.

Recently the Forest Products Laboratory completed a series of kiln runs on the heartwood and sapwood of 1- by 8-inch sugar maple primarily for the purpose of determining the effect of air velocity on drying time. The runs were made in a wind tunnel type of drying unit within which the temperature, relative humidity, and air velocity were maintained constant during each of the various runs. The boards were piled on 1-inch stickers to a width of 4 feet in the direction of air travel. The original green moisture content averaged, approximately, 70 percent and the drying period was from this condition down to a moisture content of 20 to 30 percent. Only one temperature, 130° F., was used for all runs, but the relative humidity, because of surface checking tendencies, ranged from 20 to 76 percent for the sapwood boards and from 76 to 91 percent for the heartwood boards. The air velocity ranged from 155 to 1,640 feet per minute. The data obtained in these kiln runs are presented here in discussing the seven factors enumerated in the preceding paragraph.

(1) Original and Final Moisture Content

The drying rate of a given piece of wood is proportional to the moisture gradient. By gradient is meant the rate of increase in moisture content from the surface fibers toward the center. This gradient is greatest at the beginning and, under any given relative humidity, is a maximum only when the air velocity is sufficiently high to bring the surface fibers down to a moisture content in equilibrium with the surrounding air. As the interior dries, the gradient decreases causing corresponding changes in the drying rate.

To illustrate the importance of moisture content, the average drying rate of sugar maple under a temperature of 130° F. and a relative humidity of 76 percent is given in table 1 for 10 percent moisture content changes. The highest air velocity run (1,640 feet per minute) is used to eliminate as much as possible the velocity effect.

The drying rate at any specific moisture value is influenced by the original green moisture content. For that reason a slight error is introduced in comparing the drying rates of the sapwood which has an average original moisture content of 70 percent with that of the heartwood which had an average original moisture content of 65 percent. At 55 percent moisture content, this error amounts to approximately 15 percent, but at 20 percent moisture content the error is negligible. In other words, if the average original moisture content of the heartwood had been 70 instead of 65 percent, the average drying rate between 60 and 50 percent moisture content would have been approximately 15 percent less than that shown.

Under these constant drying conditions, more time was needed to dry from 30 to 20 percent moisture content than from 70 to 30 percent. This illustrates the necessity of specifying quite definitely the moisture content limits in estimating drying time.

Table 1.--Drying time of 4/4 sugar maple under a temperature of 130° F., a relative humidity of 76 percent, and an air velocity of 1,640 feet per minute

Moisture content		Sapwood		Heartwood	
From	To	Drying time	Average moisture content loss per hour	Drying time	Average moisture content loss per hour
Percent	Percent	Hours	Percent	Hours	Percent
70	60	3.2	3.1	.....	....
60	50	4.4	2.3	6.3	1.6
50	40	6.1	1.6	10.0	1.0
40	30	10.9	.9	20.0	.5
30	20	34.9	.3	47.0	.2
60	20	56.3		83.3	

(2) Sapwood Versus Heartwood

In general, heartwood dries slower than sapwood, and in the case of the sugar maple the ratio of drying rates was approximately two-thirds. This is illustrated by the data given in table 1. Under the conditions given, the drying time from 60 to 20 percent moisture content was 83.0 hours for heartwood and 56.0 for sapwood.

(3) Temperature of Kiln Air

Only one temperature (130° F.) was used but some data on oak have indicated that between 130° and 160° F. drying rate increases approximately 2 percent for each 1 degree increase in temperature. On this basis, the sugar maple sapwood at 160° F. would dry from 60 to 20 percent moisture content in $\frac{56.3}{1.60}$ or 35 hours. This computed drying time is only an approximation and is given merely as an illustration that temperature must be considered in estimating drying time.

(4) Size of Stock

Although only one size was dried in these particular experiments, it might be well to explain how the data can be used to estimate the drying time of other sizes. Drying time is not directly proportional to thickness, but, for an infinite width, is more nearly proportional to the square of the thickness. Width is a factor also because as the width decreases the edge drying becomes relatively more important as compared to the amount of drying from the faces. A mathematical method of computing this has been used at the Laboratory and has been found to check well with empirical methods. Some of these computed ratios are shown in table 2.

Table 2.--Theoretical drying time of various sizes based on that of 1-inch stock of infinite width as unity

Thickness	Width						
	1	2	3	4	6	8	Infinite
Inches	Relative time						
1	0.50	0.80	0.90	0.94	0.97	0.99	1
2		2.00	2.77	3.20	3.60	3.77	4.00
3			4.50	5.76	7.20	7.89	9.00
4				8.00	11.08	12.80	16.00

The values show the relative drying time as compared to that of 1-inch stock of infinite width. Estimates can be made for narrow widths only when the air circulates freely around all sides. When the stock is piled edge to edge in a wide solid layer, an infinite width may be assumed.

(5) Relative Humidity of Kiln Air

Previously, it was stated that the drying rate is proportional to the moisture gradient. One factor limiting the gradient is the equilibrium moisture content at the surface of the wood and this, in turn, is a function of the relative humidity of the air. The confusing thing, however, is that the relative humidities at the surfaces and at the leaving-air side are not the same as that of the conditioned air. As heat passes from the air stream to the wood surface and is used for evaporation, a temperature drop occurs which, together with the addition of the evaporated moisture, results in an increase in relative humidity at the wood surface. The main air stream is thus affected and by the time it reaches the leaving air side, it has a lower temperature and higher relative humidity than when it entered the load. The magnitude of the difference between the air stream and the surface is governed mainly by the air velocity while that between the entering and leaving-air sides of the load is governed by the volume of air supplied and the length of air travel. Both differences (one perpendicular and one parallel to the board surfaces) are affected by the rate at which the moisture is given off.

This is illustrated graphically in figure 1. The drying data were collected from a series of heartwood runs where the relative humidity and air velocity of the individual runs were as follows: 76, 80, 86, and 91 percent at 235 feet per minute, and 76, 80, and 86 percent at 450 and 980 feet per minute. On the charts, the lines drawn through the data points were extended to the zero drying rate line at 100 percent relative humidity.

It might be well to mention here that the moisture content values identifying the curves in figures 1 to 4 are average values and that in each case a moisture gradient existed from the interior of the wood to the surface and from the entering to the leaving-air sides of the load. At the same average moisture content, differences in the slope of these gradients accounted for the differences in drying rate.

A comparison of the three charts of figure 1 shows that at 60 percent moisture content the relative humidity effect on drying rate under an air velocity of 980 feet per minute was quite different from that at 235 feet per minute. At a moisture content of 30 percent, however, the difference was very much less.

At a moisture content of 60 percent, a constant drying rate of 0.48 percent moisture content loss per hour was obtained under each of the following drying conditions, 76 percent relative humidity and 235 feet per minute air velocity, 85 percent and 450 feet per minute, and 91 percent and 980 feet per minute. Each of these three conditions, then, produced the same average effective equilibrium moisture content on the surface of the wood at that particular moisture content of stock.

Figure 2 shows the drying data for sapwood boards when dried under relative humidities from 76 down to 20 percent. The air velocity was 1,640 feet per minute, which was sufficiently high to prevent any appreciable humidity rise next to the wood surface especially at the low moisture content values. The curves, then, represent the relative humidity effect on drying rate and show how much more important it was at the higher moisture values.

The curves also show that the importance of changes in relative humidity became increasingly greater as the humidity increased above 60 or 70 percent. Below 60 percent, the humidity effect became relatively unimportant.

(6) Velocity of Kiln Air

No kiln-drying time records are complete without showing the air velocity and volume as well as the temperature and relative humidity. The importance of this is shown by the constant drying rate curves of figure 3. Each curve represents some definite drying rate of a 4-foot pile of 1- by 8-inch sugar maple sapwood boards when at 60 percent moisture content and when subjected to various combinations of air velocity and humidity. The chart shows that when the wood was at this high moisture content, the surface was subjected to the relative humidity of the conditioned air only when the air velocity was very high. Below this maximum air velocity, a constant drying rate was maintained only by lowering the relative humidity of the conditioned air.

For instance, when the stock was at 60 percent moisture content an air velocity of 1,600 feet per minute and a relative humidity of 84 resulted in a moisture loss of 2 percent per hour. When the air velocity was reduced to 400 feet per minute the relative humidity had to be reduced to 48 percent to maintain the same average drying rate. In both cases the effective average humidity at the wood surface must have been approximately 84 percent, but in the case of the lower velocity the humidity varied from the 48 percent of the conditioned air to the average of 84 percent next to the wood surface. For this reason, the results in various types of kilns apparently using the same drying schedule may vary widely because of a difference in air velocity.

The effect of air velocity on drying rate at definite moisture-content values is shown by the curves of figure 4. The obvious conclusion is that air velocity is most important at high moisture-content values, and becomes relatively unimportant below 30 percent moisture content. For thoroughly air-dried stock very little velocity is needed except to establish uniform drying conditions in all parts of the kiln.

Another important conclusion can be made from the data as presented in figure 5. This graph shows the average drying time in hours of a 4-foot wide pile of 1- by 8-inch sugar maple sapwood boards when dried from 70 to 25 percent moisture content under a constant temperature of 130° F. and under the indicated relative humidities and air velocities. The data indicate that much higher air velocities are needed for high than for low relative humidity schedules. The reason for this is that, at high humidities, changes in the equilibrium moisture content of wood become increasingly greater with unit increases in humidity, and as a result the drying rate is more affected by the changes in humidity brought about by an addition of moisture from the wood and the drop in temperature across the load.

Defining optimum air velocity as being some velocity beyond which the effect on drying time becomes relatively unimportant, the optimum values for relative humidities of 20, 50, and 76 percent might be selected from the curves of figure 5 as being 200, 400, and 800 feet per minute, respectively. Of course, for slower-drying species such as oak, these values would be lower.

(7) Length of Air Travel

As conditioned air passes through a load and heat is used for evaporation, the progressive changes in temperature and humidity result in changes in drying rate, and, therefore, in a drying lag across the load in the direction of air direction. Under otherwise fixed conditions, the amount of this lag is governed by the length of air travel, but is not directly proportional. To illustrate; data are given in table 3 to show the time to dry from 70 to 40 percent moisture content at even intervals across a 4-foot pile of 4/4 sugar maple sapwood. As the air velocity effect on the entering-air side is quite different from that on the leaving-air side, the data given are from three separate air-velocity runs.

Table 3.--Drying time of 4/4 sugar maple sapwood from 70 to 40 percent moisture content at definite intervals across a 4-foot wide pile under an entering-air temperature of 130° F. and a relative humidity of 76 percent

Air velocity	Length of air travel					Average
	0 feet (Entering air)	1 foot	2 feet	3 feet	4 feet (Leaving air)	
Feet per minute	Hours	Hours	Hours	Hours	Hours	Hours
256	15	40	54	63	69	49
545	12	24	28	30	31	27
852	10	16	19	21	22	18

The drying time lag in each run is considerably greater than that which might be expected from the average temperature drop across the load. The air, as it enters the load, is uniform in temperature and humidity, and, consequently, the velocity effect on the drying rate of the entering-air edge is relatively small. The directional force of the air, however, prevents a uniform distribution of the evaporated moisture and heat loss, and, as a result, the air at the leaving-air edge varies greatly in temperature and humidity from the wood surface to the center of the air stream. The velocity of the air influences this nonuniformity and consequently has its greatest effect on the leaving-air side.

The greatest difference in drying time occurred within the first 2 feet of the 4-foot air travel and in each of the three runs the average drying time of the full load was represented by the drying time of the wood located approximately 1.6 feet (or 0.4 of the total width) in from the entering-air side. At the high velocity this decreasing effect of length of air travel on drying time was such as to indicate that the width of load could have been considerably greater with only a small change in average drying time or in that of the leaving-air edge. The effect at the low velocity was relatively high and might be taken as suggesting the desirability of introducing several entering-air edges within the load by means of vertical flues. In other words, it suggests that two 4-foot loads of sugar maple sapwood placed side by side with a space between might have a lesser average drying time than one 8-foot load.

Aside from the velocity phase it might be well to point out here that the sapwood boards dried without checking even under a relative humidity of 20 percent and an air velocity of 1,600 feet per minute, whereas the heartwood boards checked some at a humidity as high as 80 percent. For this reason, if, in sawing and kiln drying 4/4 maple, the all-sapwood boards could be sorted from the heartwood boards and dried separately under a low relative humidity schedule then their drying time would be greatly reduced from that ordinarily allowed for log run maple.

Summary

In general, air needs are proportional to drying rates. For that reason, air needs are least for the lower moisture content stock and for the slower-drying species and items. An exception to this rule occurs when relative humidities are increased above, approximately 70 percent. Such a procedure reduces drying rate, but requires a higher air velocity to prevent excessive increases in the moisture content of the wood surface and, consequently, excessive loss of drying time. By inference, then, the most efficient kiln from a drying time standpoint would be one equipped to furnish a great deal of air at the beginning and then lesser amounts as the moisture content of stock decreases and as reductions are made in relative humidity.

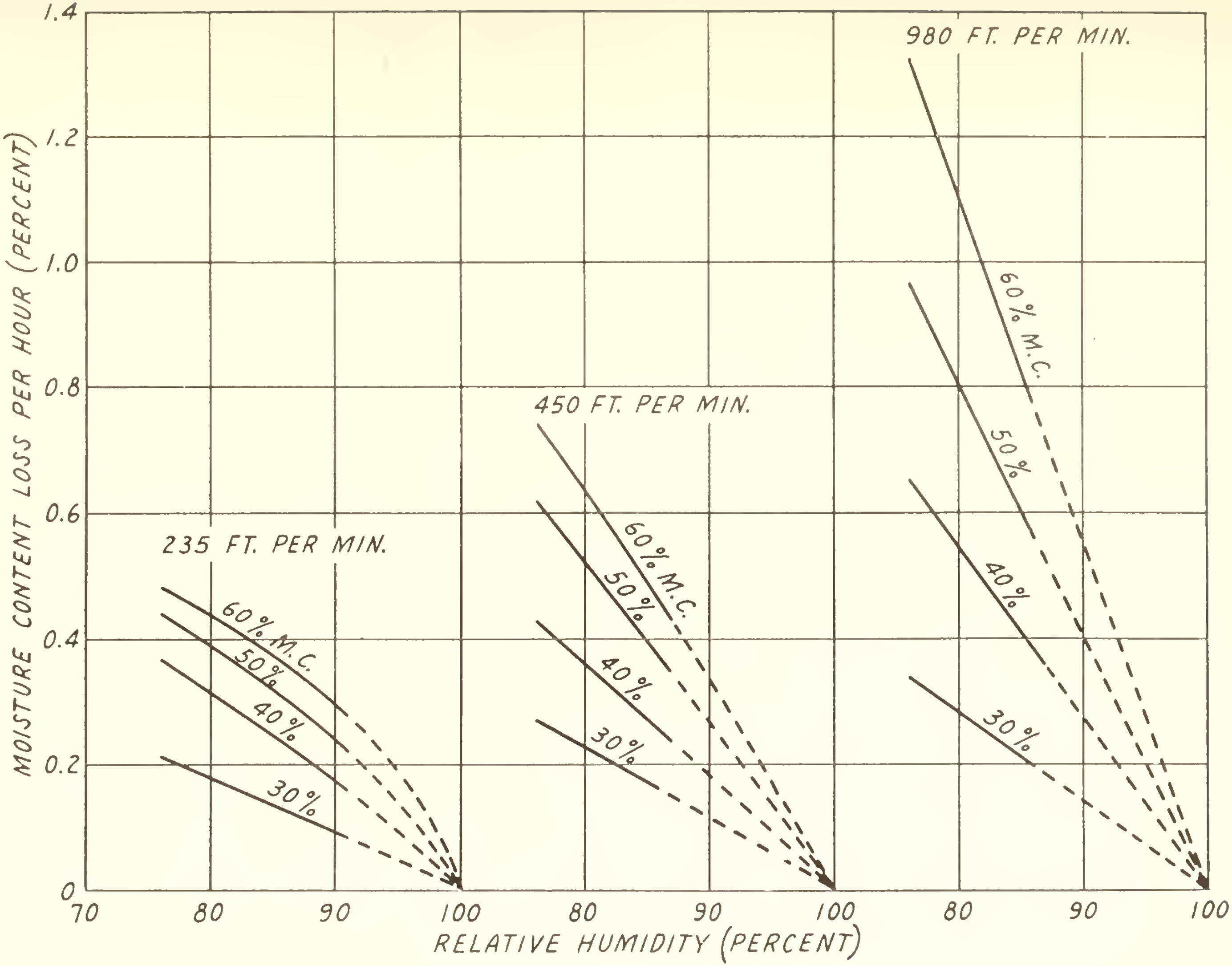

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Figure 1.--Effect of relative humidity on the drying rate of sugar maple heartwood at a temperature of 130 deg. F. and air velocities of 235, 450, and 980 feet per minute.

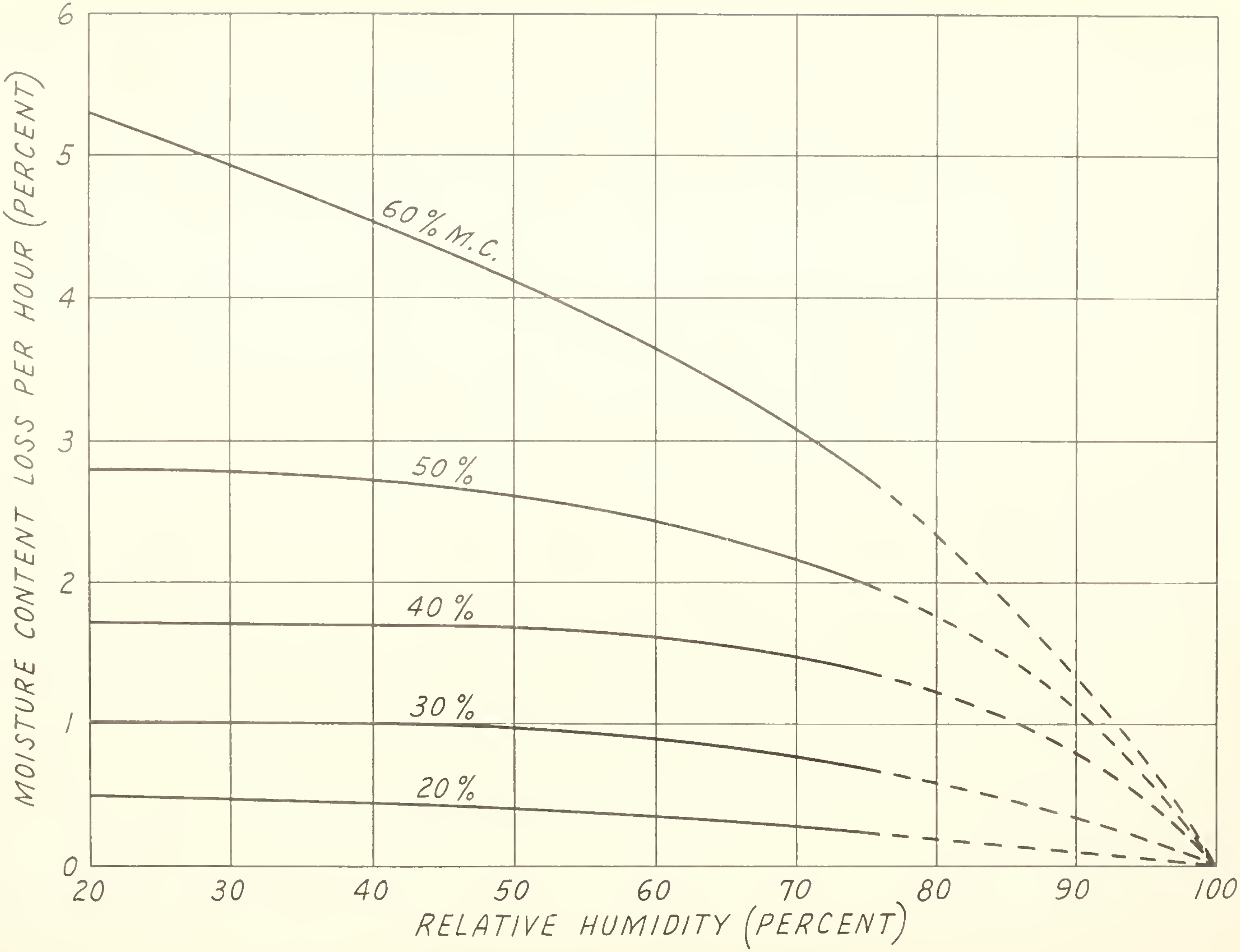

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Figure 2.--Effect of relative humidity on the drying rate of sugar maple sapwood at a temperature of 130 deg. F. and an air velocity of 1,640 feet per minute.

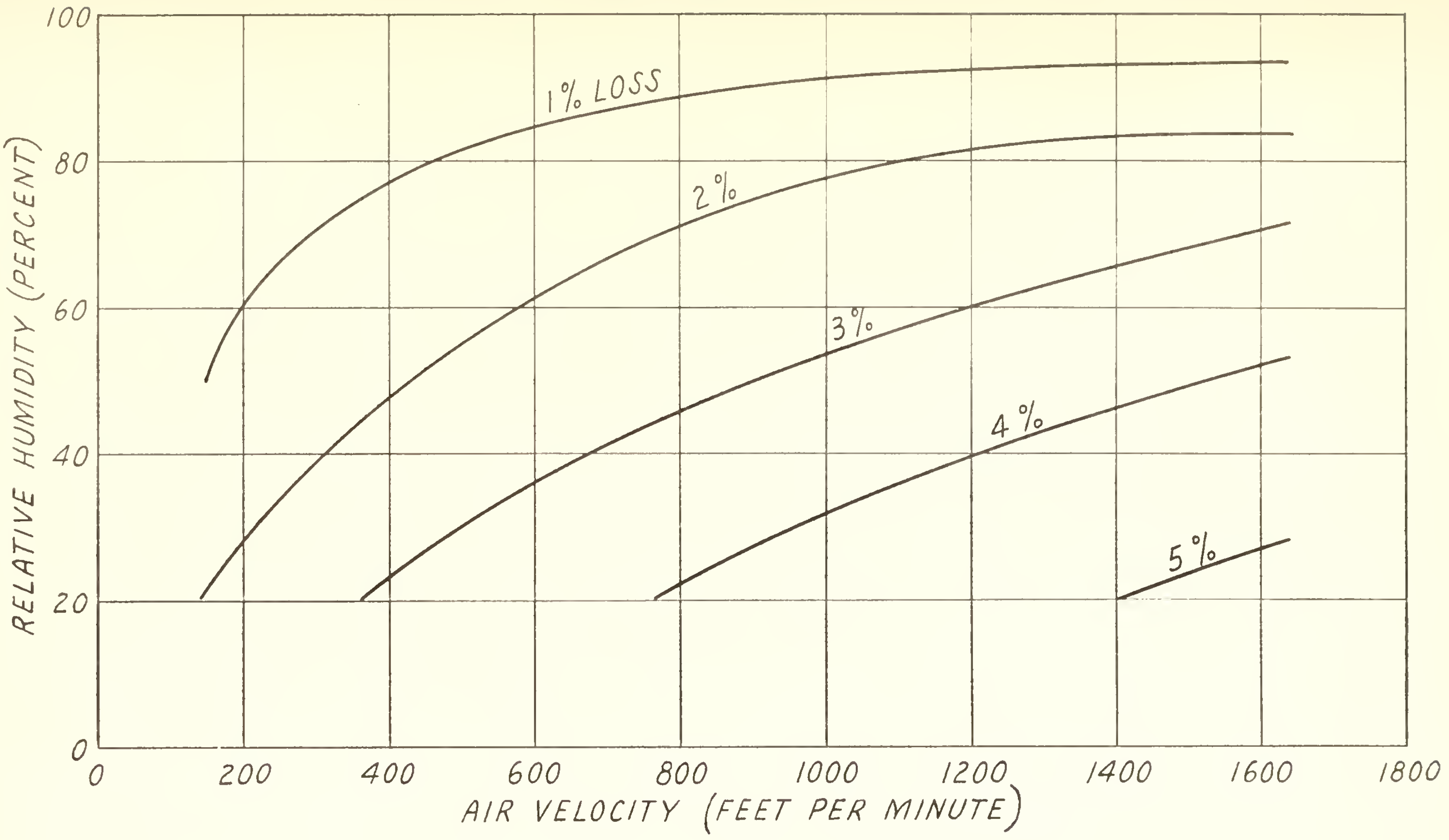

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Figure 3.--Effect of air velocity and relative humidity on the moisture content loss per hour of sugar maple sapwood when at a moisture content of 60 percent and a temperature of 130 deg. F.

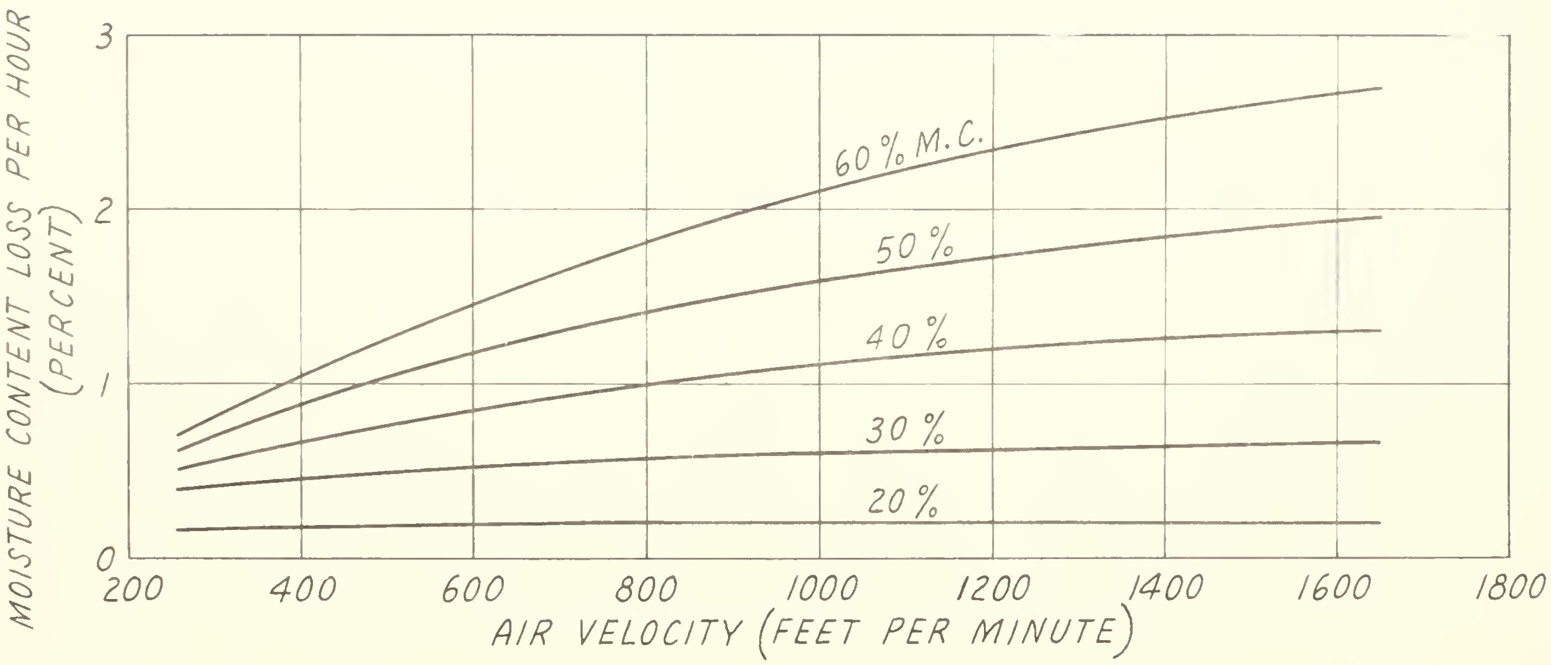

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Figure 4.--Effect of air velocity on the drying rate of sugar maple sapwood at a temperature of 130 deg. F. and a relative humidity of 76 percent.

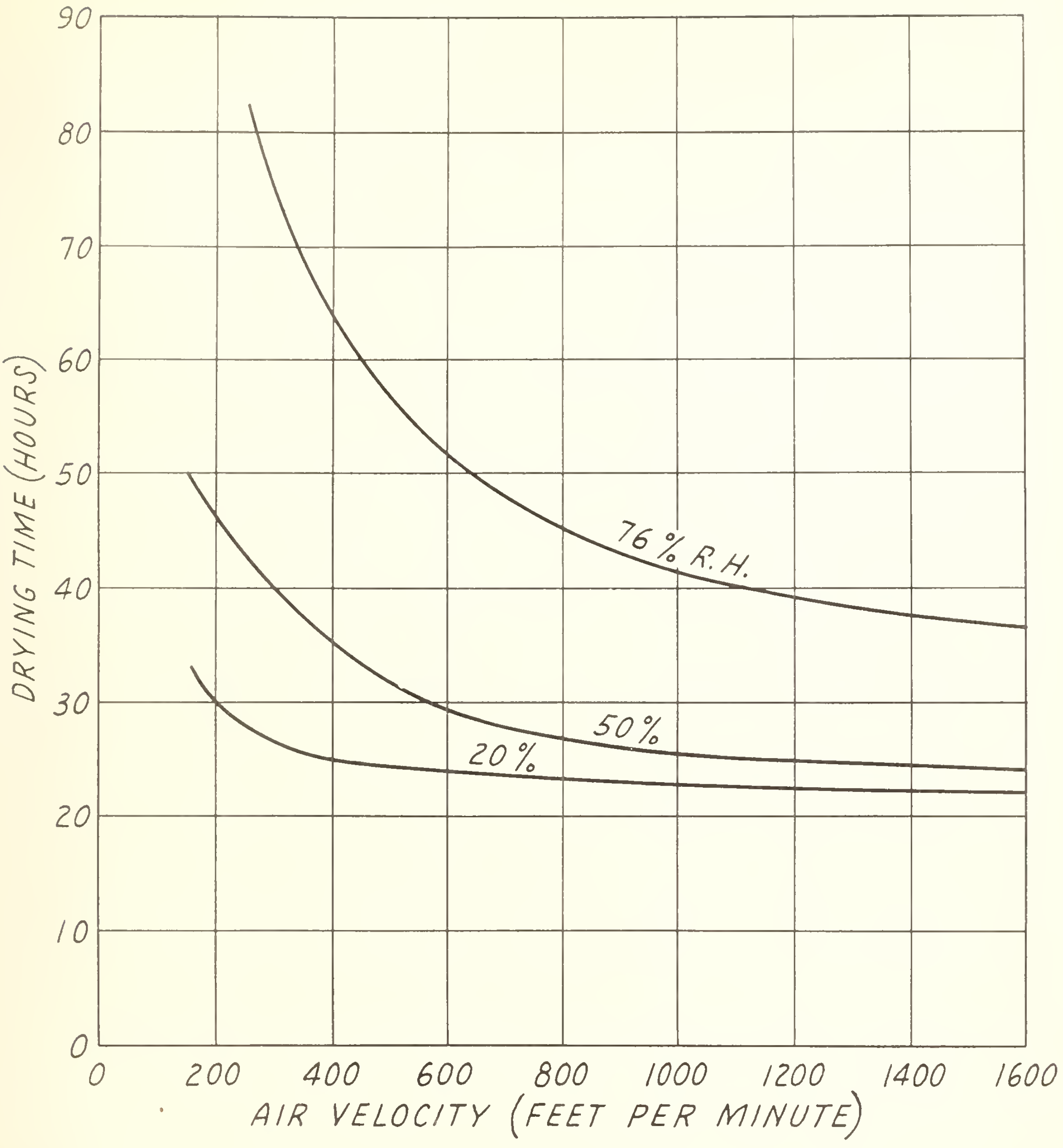

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Figure 5.--Effect of air velocity on the drying time of sugar maple sapwood in drying from 70 to 25 percent moisture content at a temperature of 130 deg. F. and relative humidities of 20, 50, and 76 percent.